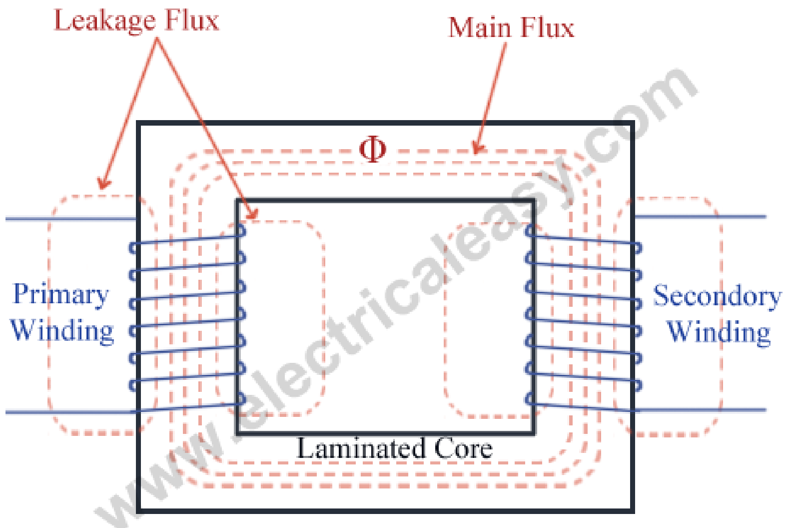
Transformer

electrical transformer is a static electrical machine which transforms electrical power from one circuit to another circuit, without changing the frequency. Transformer can increase or decrease the voltage with corresponding decrease or increase in current.

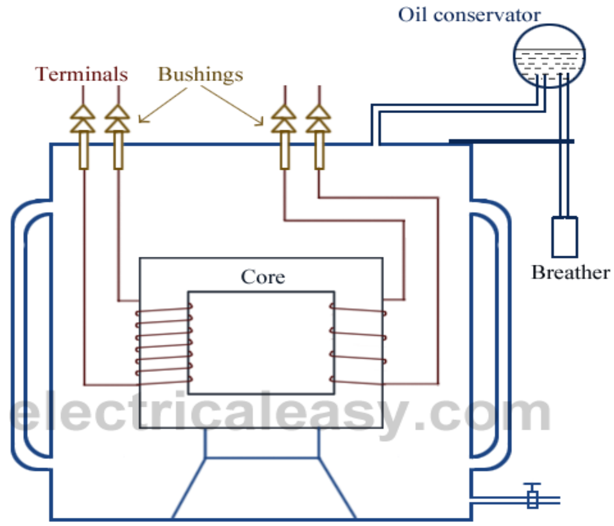
Working principle of transformer



The **basic principle behind working of a transformer** is the phenomenon of mutual induction between two windings linked by common magnetic flux. The figure at right shows the simplest form of a transformer. Basically a transformer consists of two inductive coils; primary winding and secondary winding. The coils are electrically separated but magnetically linked to each other. When, primary winding is connected to a source of alternating voltage, alternating magnetic flux is produced around the winding. The core provides magnetic path for the flux, to get linked with the secondary winding. Most of the flux gets linked with the secondary winding which is called as 'useful flux' or main 'flux', and the flux which does not get linked with secondary winding is called as 'leakage flux'. As the flux produced is alternating (the direction of it is continuously changing), EMF gets induced in the secondary winding according to Faraday's law of electromagnetic induction. This emf is called 'mutually induced emf', and the frequency of mutually induced emf is same as that of supplied emf. If the secondary winding is closed circuit, then mutually induced current flows through it, and hence the electrical energy is transferred from one circuit (primary) to another circuit (secondary).

Basic construction of transformer

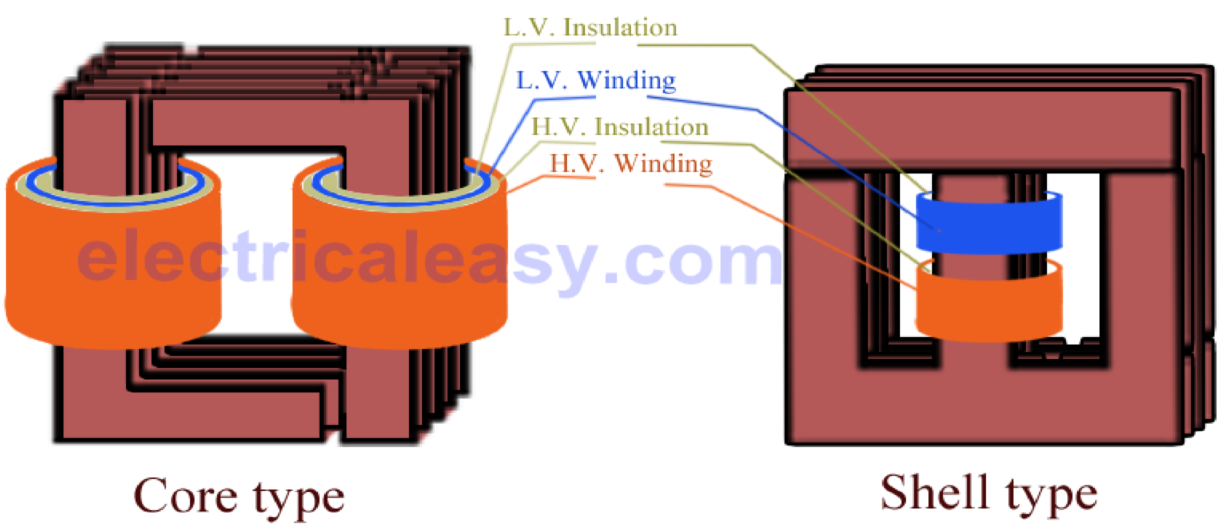
Basically a transformer consists of two inductive windings and a laminated steel core. The coils are insulated from each other as well as from the steel core. A transformer may also consist of a container for winding and core assembly (called as tank), suitable bushings to take our the terminals, oil conservator to provide oil in the transformer tank for cooling purposes etc. The figure at left illustrates the basic construction of a transformer. In all types of transformers, core is constructed by assembling (stacking) laminated sheets of steel, with minimum air-gap between them (to achieve continuous magnetic path). The steel used is having high silicon content and sometimes heat treated, to provide high permeability and low hysteresis loss. Laminated sheets of steel are used to reduce eddy current loss. The sheets are cut in the shape as E,I and L. To avoid high reluctance at joints, laminations are stacked by alternating the sides of joint. That is, if joints of first sheet assembly are at front face, the joints of following assemble are kept at back face.



Types of transformers
Transformers can be classified on different basis, like types of construction, types of cooling etc.

(A) On the basis of construction, transformers can be classified into two types as;

(i) Core type transformer and (ii) Shell type transformer, which are described below.



(i) Core type transformer
In core type transformer, windings are cylindrical former wound, mounted on the core limbs as shown in the figure above. The cylindrical coils have different layers and each layer is insulated from each other. Materials like paper, cloth or mica can be used for insulation. Low voltage windings are placed nearer to the core, as they are easier to insulate.

(ii) Shell type transformer

The coils are former wound and mounted in layers stacked with insulation between them. A shell type transformer may have simple rectangular form (as shown in above fig), or it may have a distributed form.

(B) On the basis of their purpose

1. Step up transformer: Voltage increases (with subsequent decrease in current) at secondary.
2. Step down transformer: Voltage decreases (with subsequent increase in current) at secondary.

(C) On the basis of type of supply

1. Single phase transformer
2. Three phase transformer
3.

(D) On the basis of their use

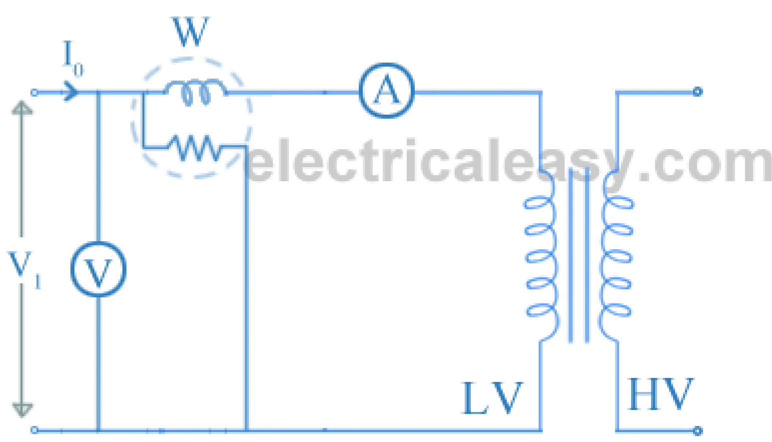
1. Power transformer: Used in transmission network, high rating
2. Distribution transformer: Used in distribution network, comparatively lower rating than that of power transformers.
3. Instrument transformer: Used in relay and protection purpose in different instruments in industries
   - Current transformer (CT)
   - Potential transformer (PT)
   -

Open circuit and Short circuit Test on transformer

These two transformer tests are performed to find the parameters of equivalent circuit of transformer and losses of the transformer. Open circuit test and short circuit test on transformer are very economical and convenient because they are performed without actually loading of the transformer.

Open circuit or No load test on Transformer

Open circuit test or no load test on a transformer is performed to determine 'no load loss (core loss)' and 'no load current I_0'. The circuit diagram for open circuit test is shown in the figure below.



Usually high voltage (HV) winding is kept open and the low voltage (LV) winding is connected to its normal supply. A wattmeter (W), ammeter (A) and voltmeter (V) are connected to the LV winding as shown in the figure. Now, applied voltage is slowly increased from zero to normal rated value of the LV side with the help of a variac. When the applied voltage reaches to the rated value of the LV winding, readings from all the three instruments are taken.

The ammeter reading gives the no load current I_0. As I_0 itself is very small, the voltage drops due to this current can be neglected.

The input power is indicated by the wattmeter (W). And as the other side of transformer is open circuited, there is no output power. Hence, this input power only consists of core losses and copper losses. As described above, no-load current is so small that these copper losses can be neglected. Hence, now the input power is almost equal to the core losses. Thus, the wattmeter reading gives the core losses of the transformer.

Sometimes, a high resistance voltmeter is connected across the HV winding. Though, a voltmeter is connected, HV winding can be treated as open circuit as the current through the voltmeter is negligibly small. This helps in to find voltage transformation ratio (K).

The two components of no load current can be given as,

$I_\mu = I_0 \sin\Phi_0$ and $I_w = I_0 \cos\Phi_0$.
$\cos\Phi_0$ (no load power factor) = $W / (V_1 I_0)$. ... (W = wattmeter reading)

From this, shunt parameters of equivalent circuit parameters of equivalent circuit of transformer (X_0 and R_0) can be calculated as

$X_0 = V_1/I_\mu$ and $R_0 = V_1/I_w$.

(These values are referring to LV side of the transformer.)
Hence, it is seen that **open circuit test** gives core losses of transformer and shunt parameters of the equivalent circuit.

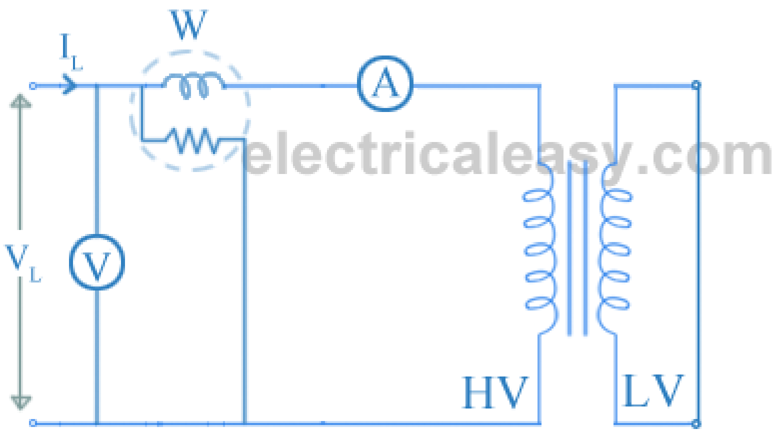
Short circuit or Impedance test on Transformer

The **connection diagram for short circuit test** or impedance test on transformer is as shown in the figure below. The LV side of transformer is short circuited and wattmeter (W), voltmere (V) and ammeter (A) are connected on the HV side of the transformer. Voltage is applied to the HV side and increased from the zero until the ammeter reading equals the rated current. All the readings are taken at this rated current.

The ammeter reading gives primary equivalent of full load current (I_{sc}).
The voltage applied for full load current is very small as compared to rated voltage. Hence, core loss due to small applied voltage can be neglected. Thus, the wattmeter reading can be taken as copper loss in the transformer.

Therefore, $W = I_{sc}^2 R_{eq}$....... (where R_{eq} is the equivalent resistance of transformer)
$Z_{eq} = V_{sc}/I_{sc}$.
Therefore, equivalent reactance of transformer can be calculated from the formula $Z_{eq}^2 = R_{eq}^2 + X_{eq}^2$.
These, values are referred to the HV side of the transformer.
Hence, it is seen that the short circuit test gives copper losses of transformer and approximate equivalent

resistance and reactance of the transformer.



Why Transformers are rated in kVA?
From the above transformer tests, it can be seen that Cu loss of a transformer depends on current, and iron loss depends on voltage. Thus, total transformer loss depends on volt-ampere (VA). It does not depend on the phase angle between voltage and current, i.e. transformer loss is independent of load power factor. This is the reason that transformers are rated in kVA.

Losses in transformer

In any electrical machine, 'loss' can be defined as the difference between input power and output power.
An electrical transformer is an static device, hence mechanical losses (like windage or friction losses) are absent in it. A transformer only consists of electrical losses (iron losses and copper losses). Transformer losses are similar to losses in a DC machine, except that transformers do not have mechanical losses.
Losses in transformer are explained below -

(i) Core losses or Iron losses
Eddy current loss and hysteresis loss depend upon the magnetic properties of the material used for the construction of core. Hence these losses are also known as **core losses** or **iron losses**.

- **Hysteresis loss in transformer**: Hysteresis loss is due to reversal of magnetization in the transformer core. This loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density. It can be given by, Steinmetz formula:
  $W_h = \eta B_{max}^{1.6} f V$ (watts)
  where, η = Steinmetz hysteresis constant
  V = volume of the core in m^3
- **Eddy current loss in transformer**: In transformer, AC current is supplied to the primary winding which sets up alternating magnetizing flux. When this flux links with secondary winding, it produces induced emf in it. But some part of this flux also gets linked with other conducting parts like steel core or iron body or the transformer, which will result in induced emf in those parts, causing small circulating current in them. This current is called as eddy current. Due to these eddy currents, some energy will be dissipated in the form of heat.

(ii) Copper loss in transformer
Copper loss is due to ohmic resistance of the transformer windings. Copper loss for the primary winding is $I_1^2R_1$ and for secondary winding is $I_2^2R_2$. Where, I_1 and I_2 are current in primary and secondary winding

respectively, R_1 and R_2 are the resistances of primary and secondary winding respectively. It is clear that Cu loss is proportional to square of the current, and current depends on the load. Hence copper loss in transformer varies with the load.

Efficiency of Transformer

Just like any other electrical machine, **efficiency of a transformer** can be defined as the output power divided by the input power. That is efficiency = output / input .

Transformers are the most highly efficient electrical devices. Most of the transformers have full load efficiency between 95% to 98.5% . As a transformer being highly efficient, output and input are having nearly same value, and hence it is impractical to measure the efficiency of transformer by using output / input. A better method to find efficiency of a transformer is using, efficiency = (input - losses) / input = 1 - (losses / input).

Condition for maximum efficiency

Let,

Copper loss = I12R1

Iron loss = Wi

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2R_1 + W_i}{V_1I_1\cos\Phi_1}$$

$$\eta = 1 - \frac{I_1R_1}{V_1\cos\Phi_1} - \frac{W_i}{V_1I_1\cos\Phi_1}$$

differentiating above equation with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1\cos\Phi_1} + \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

η will be maximum at $\frac{d\eta}{dI_1} = 0$

Hence efficiency η will be maximum at

$$\frac{R_1}{V_1\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$\frac{I_1^2R_1}{V_1I_1^2\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$I_1^2R_1 = W_i$$

Hence, **efficiency of a transformer** will be maximum when copper loss and iron losses are equal.
That is Copper loss = Iron loss.

All day efficiency of transformer

As we have seen above, ordinary or commercial efficiency of a transformer can be given as

$$\text{ordinary efficiency} = \frac{\text{output (in watts)}}{\text{input (in watts)}}$$

But in some types of transformers, their performance can not be judged by this efficiency. For example, distribution transformers have their primaries energized all the time. But, their secondaries supply little load all no-load most of the time during day (as residential use of electricity is observed mostly during evening till midnight).
That is, when secondaries of transformer are not supplying any load (or supplying only little load), then only core losses of transformer are considerable and copper losses are absent (or very little). Copper losses are considerable only when transformers are loaded. Thus, for such transformers copper losses are relatively less important. The performance of such transformers is compared on the basis of energy consumed in one day.

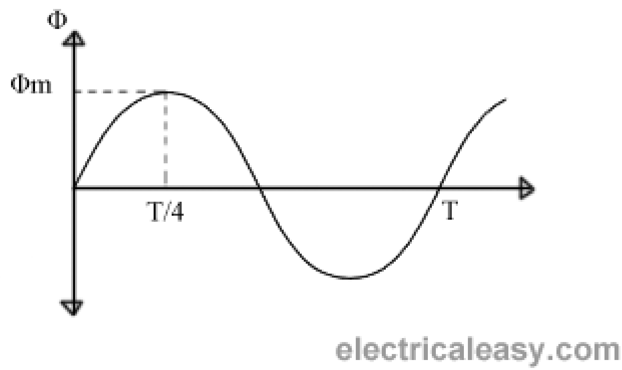
$$\text{All day efficiency} = \frac{\text{output (in kWh)}}{\text{input (in kWh)}} \quad \text{(for 24 hours)}$$

All day efficiency of a transformer is always less than ordinary efficiency of it

EMF equation of a transformer and Voltage Transformation Ratio

In a transformer, source of alternating current is applied to the primary winding. Due to this, the current in the primary winding (called as magnetizing current) produces alternating flux in the core of transformer. This alternating flux gets linked with the secondary winding, and because of the phenomenon of mutual induction an emf gets induced in the secondary winding. Magnitude of this induced emf can be found by using the following **EMF equation of the transformer**.
EMF equation of the Transformer

Let,
N_1 = Number of turns in primary winding
N_2 = Number of turns in secondary winding
Φ_m = Maximum flux in the core (in Wb) = (B_m x A)
f = frequency of the AC supply (in Hz)



As, shown in the fig., the flux rises sinusoidally to its maximum value Φ_m from 0. It reaches to the maximum value in one quarter of the cycle i.e in T/4 sec (where, T is time period of the sin wave of the supply = 1/f).
Therefore,
average rate of change of flux = $\Phi_m / _{(T/4)}$ = $\Phi_m / _{(1/4f)}$
Therefore,
average rate of change of flux = $4f\ \Phi_m$ .... (Wb/s).
Now,
Induced emf per turn = rate of change of flux per turn

Therefore, average emf per turn = $4f\ \Phi_m$ ....(Volts). Now, we know, Form factor = RMS value / average value
Therefore, RMS value of emf per turn = Form factor X average emf per turn.

As, the flux Φ varies sinusoidally, form factor of a sine wave is 1.11

Therefore, RMS value of emf per turn = $1.11 \times 4f\ \Phi_m = 4.44f\ \Phi_m$.

RMS value of induced emf in whole primary winding (E_1) = RMS value of emf per turn X Number of turns in primary winding

$E_1 = 4.44f\ N_1\ \Phi_m$ .... eq 1

Similarly, RMS induced emf in secondary winding (E_2) can be given as

$E_2 = 4.44f\ N_2\ \Phi_m$. .... eq 2

from the above equations 1 and 2,

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44f\ \Phi m$$

This is called the **emf equation of transformer**, which shows, emf / number of turns is same for both primary and secondary winding.

For an ideal transformer on no load, $E_1 = V_1$ and $E_2 = V_2$.
where, V_1 = supply voltage of primary winding
V_2 = terminal voltage of secondary winding

Voltage Transformation Ratio (K)
As derived above,

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = K$$

Where, K = constant
This constant K is known as **voltage transformation ratio**.

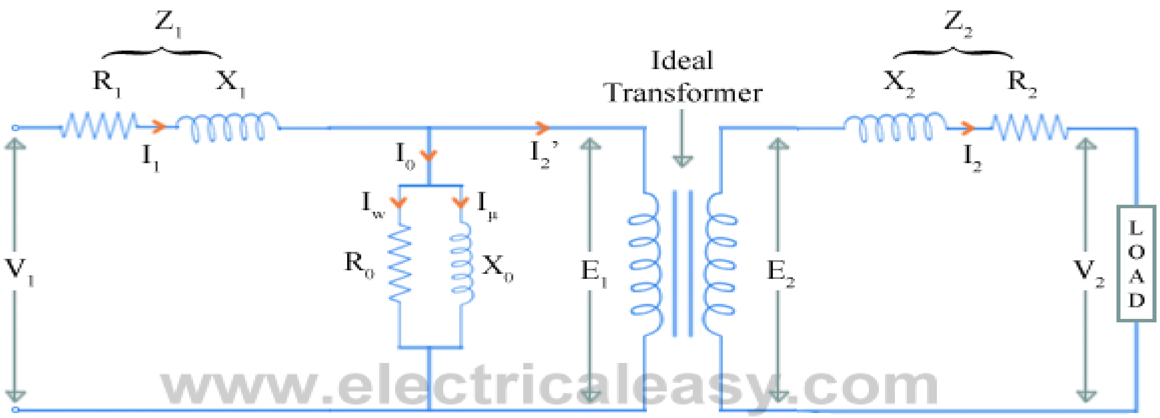
- If $N_2 > N_1$, i.e. $K > 1$, then the transformer is called step-up transformer.
- If $N_2 < N_1$, i.e. $K < 1$, then the transformer is called step-down transformer.
-

Equivalent circuit of Transformer

n a practical transformer -
(a) Some leakage flux is present at both primary and secondary sides. This leakage gives rise to leakage reactances at both sides, which are denoted as X_1 and X_2 respectively.
(b) Both the primary and secondary winding possesses resistance, denoted as R_1 and R_2 respectively. These resistances causes voltage drop as, I_1R_1 and I_2R_2 and also copper loss $I_1^2R_1$ and $I_2^2R_2$.
(c) Permeability of the core can not be infinite, hence some magnetizing current is needed. Mutual flux also causes core loss in iron parts of the transformer.

Equivalent circuit of transformer

Resistances and reactances of transformer, which are described above, can be imagined separately from the windings (as shown in the figure below). Hence, the function of windings, thereafter, will only be the transforming the voltage.



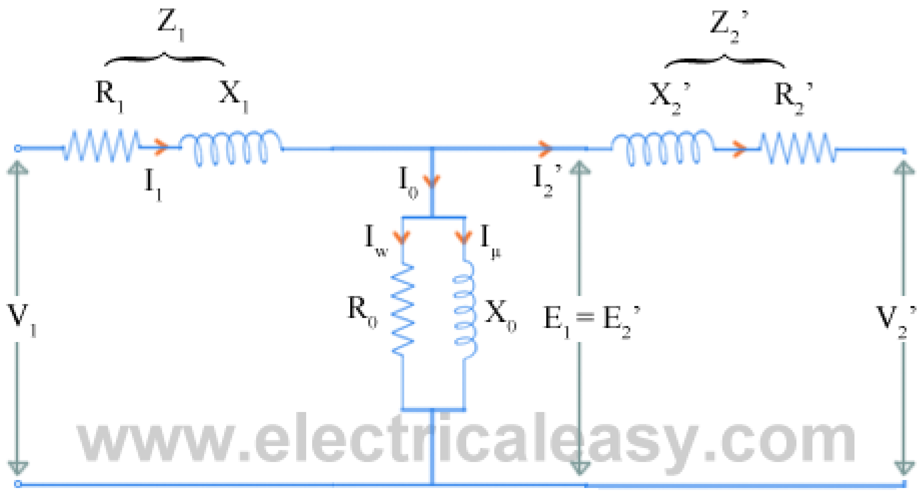
The no load current I_0 is divided into, pure inductance X_0 (taking magnetizing components I_μ) and non induction resistance R_0 (taking working component I_w) which are connected into parallel across the primary.

The value of E_1 can be obtained by subtracting I_1Z_1 from V_1. The value of R_0 and X_0 can be calculated as, $R_0 = E_1 / I_w$ and $X_0 = E_1 / I_\mu$.

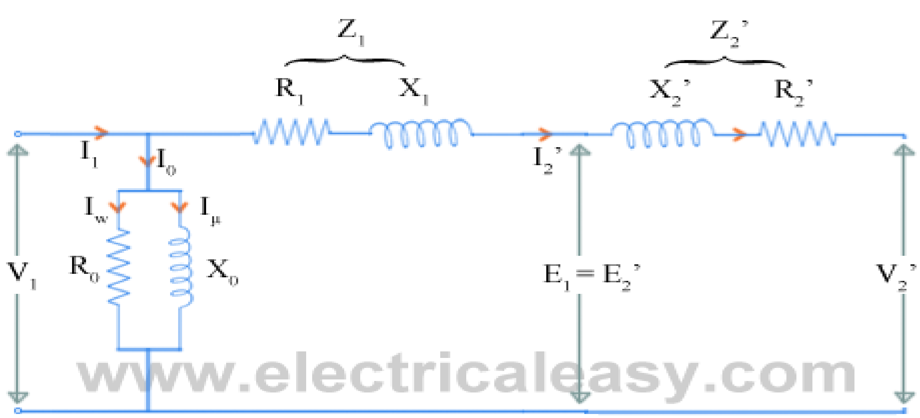
But, using this equivalent circuit does not simplifies the calculations. To make calculations simpler, it is preferable to transfer current, voltage and impedance either to primary side or to the secondary side. In that case, we would have to work with only one winding which is more convenient.

From the voltage transformation ratio, it is clear that,
$E_1 / E_2 = N_1 / N_2 = K$

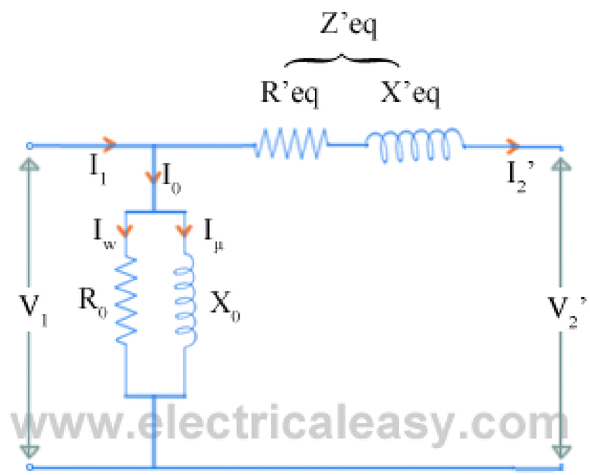
Now, lets refer the parameters of secondary side to primary.
Z_2 can be referred to primary as Z_2'
where, $Z_2' = (N_1/N_2)^2 Z_2 = K^2 Z_2$. ....where $K= N_1/N_2$.
that is, $R_2'+jX_2' = K^2(R_2+jX_2)$
equating real and imaginary parts,
$R_2' = K^2 R_2$ and $X_2' = K^2 X_2$.
And $V_2' = KV_2$
The following figure shows the **equivalent circuit of transformer with secondary parameters referred to the primary**.



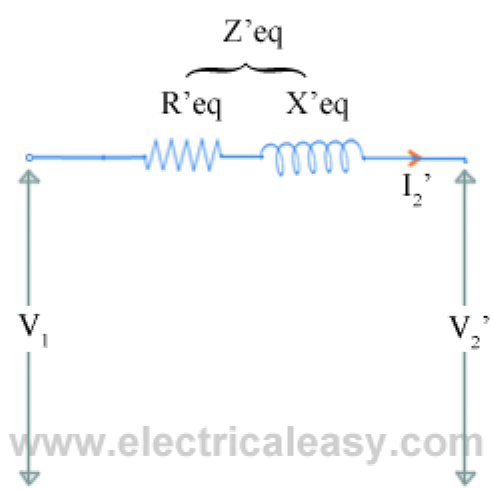
Now, as the values of winding resistance and leakage reactance are so small that, V_1 and E_1 can be assumed to be equal. Therefore, the exciting current drawn by the parallel combination of R_0 and X_0 would not affect significantly, if we move it to the input terminals as shown in the figure below.



Now, let $R_1 + R_2' = R'eq$ and $X_1 + X_2' = X'eq$
Then the **equivalent circuit of transformer** becomes as shown in the figure below



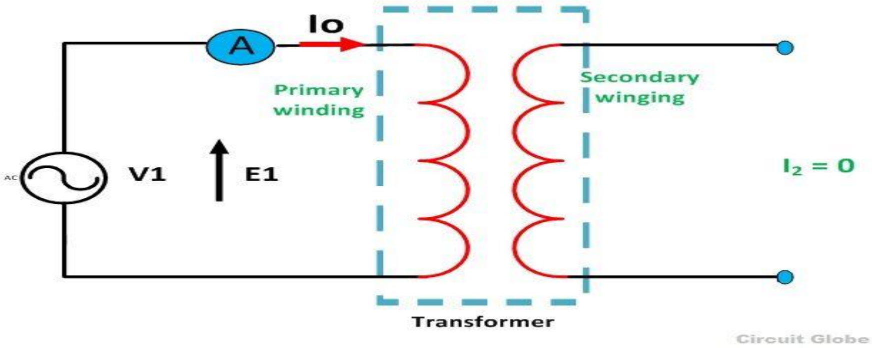
Approximate equivalent circuit of transformer
If only voltage regulation is to be calculated, then even the whole excitation branch (parallel combination of R0 and X0) can be neglected. Then the equivalent circuit becomes as shown in the figure below



Transformer on No Load Condition

When the transformer is operating at no load, the secondary winding is open-circuited, which means there is no load on the secondary side of the transformer and, therefore, current in the secondary will be zero. While primary winding carries a small current I_0 called no-load current which is **2 to 10% of the rated current**.

This current is responsible for supplying the iron losses (hysteresis and eddy current losses) in the core and a very small amount of copper losses in the primary winding. The angle of lag depends upon the losses in the transformer. The power factor is very low and varies from **0.1 to 0.15**.



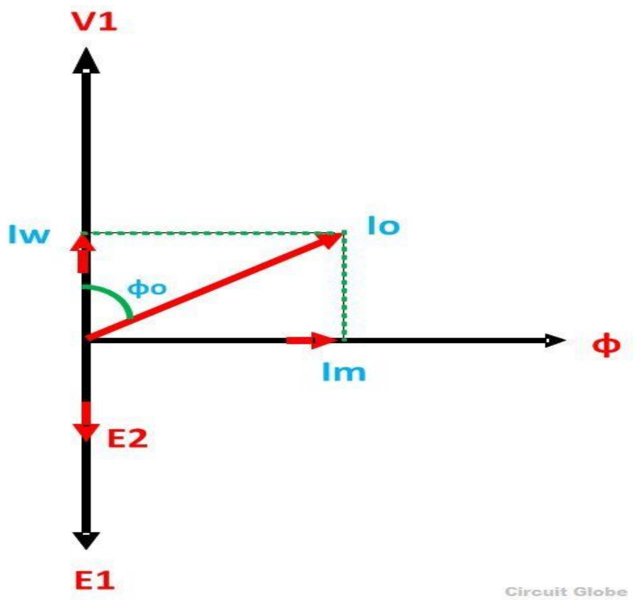
The no-load current consists of two components:

- **Reactive or magnetizing component I_m**
  (It is in quadrature with the applied voltage V_1. It produces flux in the core and does not consume any power).

- **Active or power component I_w**, also know as a working component
  (It is in phase with the applied voltage V_1. It supplies the iron losses and a small amount of primary copper loss).

  The following steps are given below to draw the phasor diagram:

1. The function of the magnetizing component is to produce the magnetizing flux, and thus, it will be in phase with the flux.
2. Induced emf in the primary and the secondary winding lags the flux ϕ by 90 degrees.
3. The primary copper loss is neglected, and secondary current losses are zero as
   $I_2 = 0$.
   Therefore, the current I_0 lags behind the voltage vector V_1 by an angle ϕ_0 called the no-load power factor angle and is shown in the phasor diagram above.
4. The applied voltage V_1 is drawn equal and opposite to the induced emf E_1 because the difference between the two, at no load, is negligible.
5. Active component I_w is drawn in phase with the applied voltage V_1.
6. The phasor sum of magnetizing current I_m and the working current I_w gives the no-load current I_0.

7. 

From the phasor diagram drawn above, the following

Working component $I_w = I_0 \cos\varphi_0$

No load current $I_0 = \sqrt{I_w^2 + I_m^2}$

Magnetizing component $I_m = I_0 \sin\varphi_0$

Power factor $\cos\varphi_0 = \frac{I_w}{I_0}$

No load power input $P_0 = V_1 I_0 \cos\varphi_0$

conclusions are made

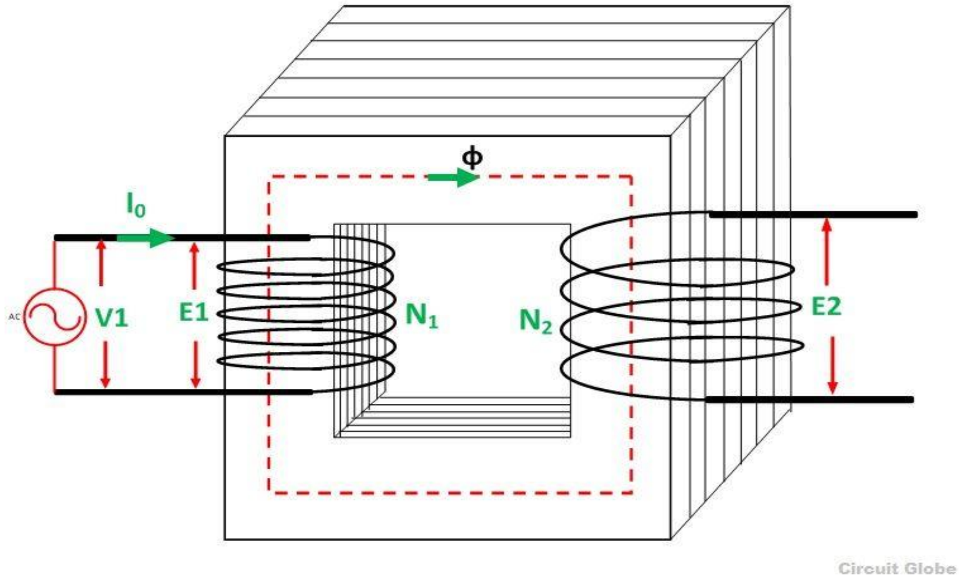
Transformer On Load Condition

When the transformer is on the loaded condition, the secondary of the transformer is connected to load. The load can be resistive, inductive or capacitive. The current I_2 flows through the secondary winding of the transformer. The magnitude of the secondary current depends on the terminal voltage V_2 and the load impedance. The phase angle between the secondary current and voltage depends on the nature of the load.

Operation of the Transformer on Load Condition

The Operation of the Transformer on Load Condition is explained below:

- When the secondary of the transformer is kept open, it draws the no-load current from the main supply. The no-load current induces the magnetomotive force N_0I_0 and this force set up the flux Φ in the core of the transformer. The circuit of the transformer at no load condition is shown in the figure below:



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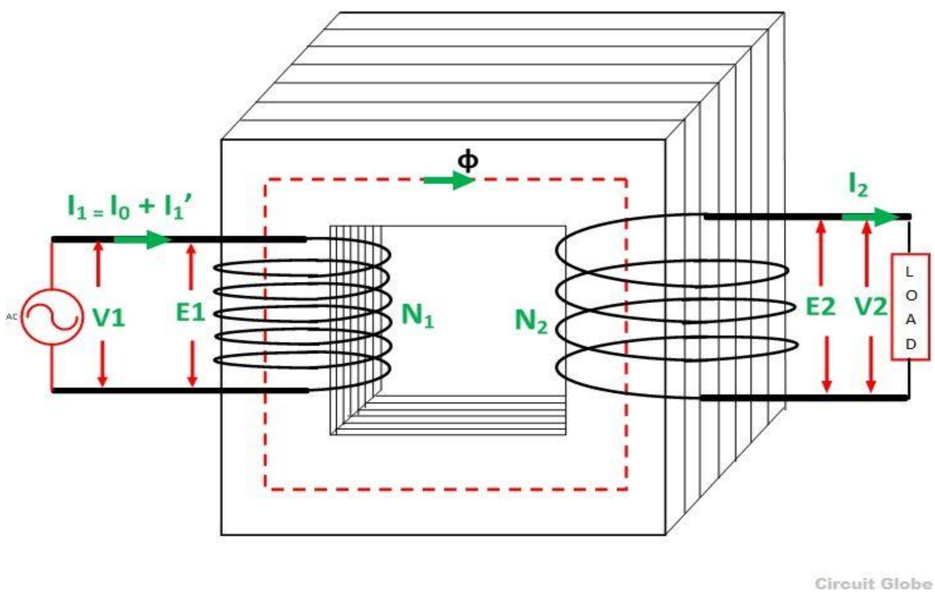
  - When the load is connected to the secondary of the transformer, I_2 current flows through their secondary winding. The secondary current induces the magnetomotive force N_2I_2 on the secondary winding of the transformer. This force set up the flux φ_2 in the transformer core. The flux φ_2 opposes the flux φ, according to **Lenz's law**.



- As the flux φ_2 opposes the flux φ, the resultant flux of the transformer decreases and this flux reduces the induced EMF E_1. Thus, the strength of the V_1 is more than E_1 and an additional primary current I'_1 drawn from the main supply.
  The additional current is used for restoring the original value of the flux in the core of the transformer so that $V_1 = E_1$. The primary current I'_1 is in phase opposition with the secondary current I_2. Thus, it is called the **primary counter-balancing current**.
- The additional current I'_1 induces the magnetomotive force $N_1I'_1$. And this force set up the flux φ'_1. The direction of the flux is the same as that of the φ and it cancels the flux φ_2 which induces because of the MMF N_2I_2

Now, $N_1I_1' = N_2I_2$

$$I_1' = \left(\frac{N_2}{N_1}\right) I_2 = KI_2$$

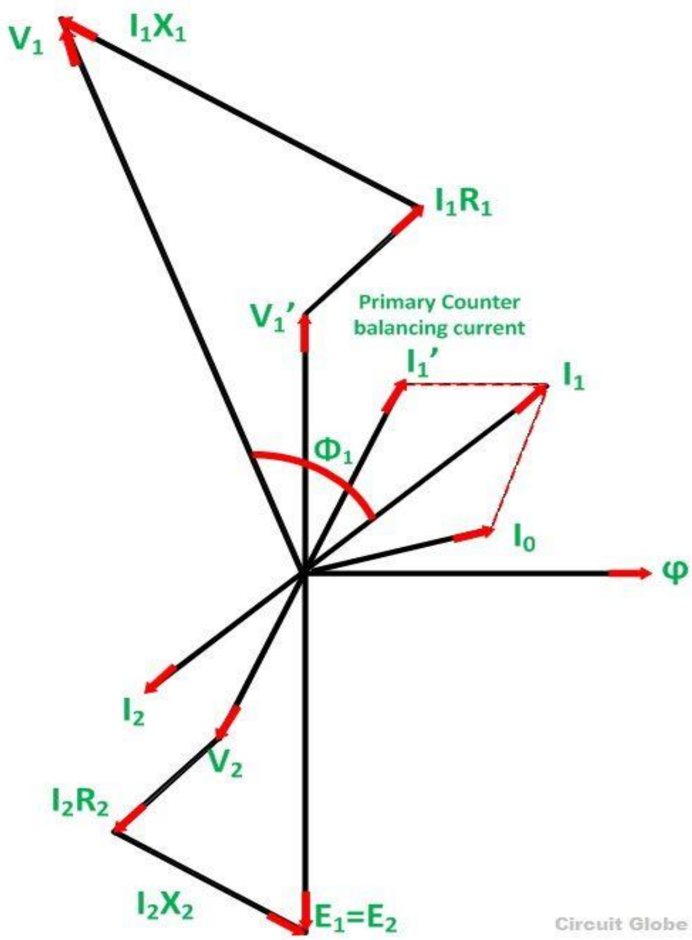
Therefore,

- The phase difference between V_1 and I_1 gives the power factor angle ϕ_1 of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.
- If the load is inductive as shown in the above phasor diagram, the power factor will be lagging, and if the load is capacitive, the power factor will be leading. The total primary current I_1 is the vector sum of the currents I_0 and I_1'. i.e

$$\overline{I_1} = \overline{I_0} + \overline{I_1'}$$

Phasor Diagram of Transformer on Inductive Load

The phasor diagram of the actual transformer when it is loaded inductively is shown below:



Phasor Diagram of the Transformer on Inductive Load

Steps to draw the phasor diagram

- Take flux ϕ, a reference
- Induces emf E_1 and E_2 lags the flux by 90 degrees.
- The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding. E_1 is represented by V_1'.
- Current I_0 lags the voltage V_1' by 90 degrees.
- The power factor of the load is lagging. Therefore current I_2 is drawn lagging E_2 by an angle ϕ_2.
- The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V_2 is the phase difference of E_2 and voltage drop.

$V_2 = E_2$ – voltage drops
$I_2 R_2$ is in phase with I_2 and I_2X_2 is in quadrature with I_2.

- The total current flowing in the primary winding is the phasor sum of I_1' and I_0.
- Primary applied voltage V_1 is the phasor sum of V_1' and the voltage drop in the primary winding.
- Current I_1' is drawn equal and opposite to the current I_2

$V_1 = V_1'$ + voltage drop
I_1R_1 is in phase with I_1 and I_1X_I is in quadrature with I_1.

- The phasor difference between V_1 and I_1 gives the power factor angle ϕ_1 of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.
- If the load is inductive as shown in the above phasor diagram, the power factor will be lagging, and if the load is capacitive, the power factor will be leading. Where I_1R_1 is the resistive drop in the primary windings I_2X_2 is the reactive drop in the secondary winding

Similarly

Phasor Diagram of Transformer on Capacitive Load

The Transformer on the Capacitive load (leading power factor load) is shown below in the phasor diagram.

Steps to draw the phasor diagram at capacitive load

- Take flux ϕ a reference
- Induces emf E_1 and E_2 lags the flux by 90 degrees.
- The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding. E_1 is represented by V_1'.
- Current I_0 lags the voltage V_1' by 90 degrees.
- The power factor of the load is leading. Therefore current I_2 is drawn leading E_2
- The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V_2 is the phasor difference of E_2 and voltage drop.

$V_2 = E_2$ – voltage drops
$I_2 R_2$ is in phase with I_2 and I_2X_2 is in quadrature with I_2.

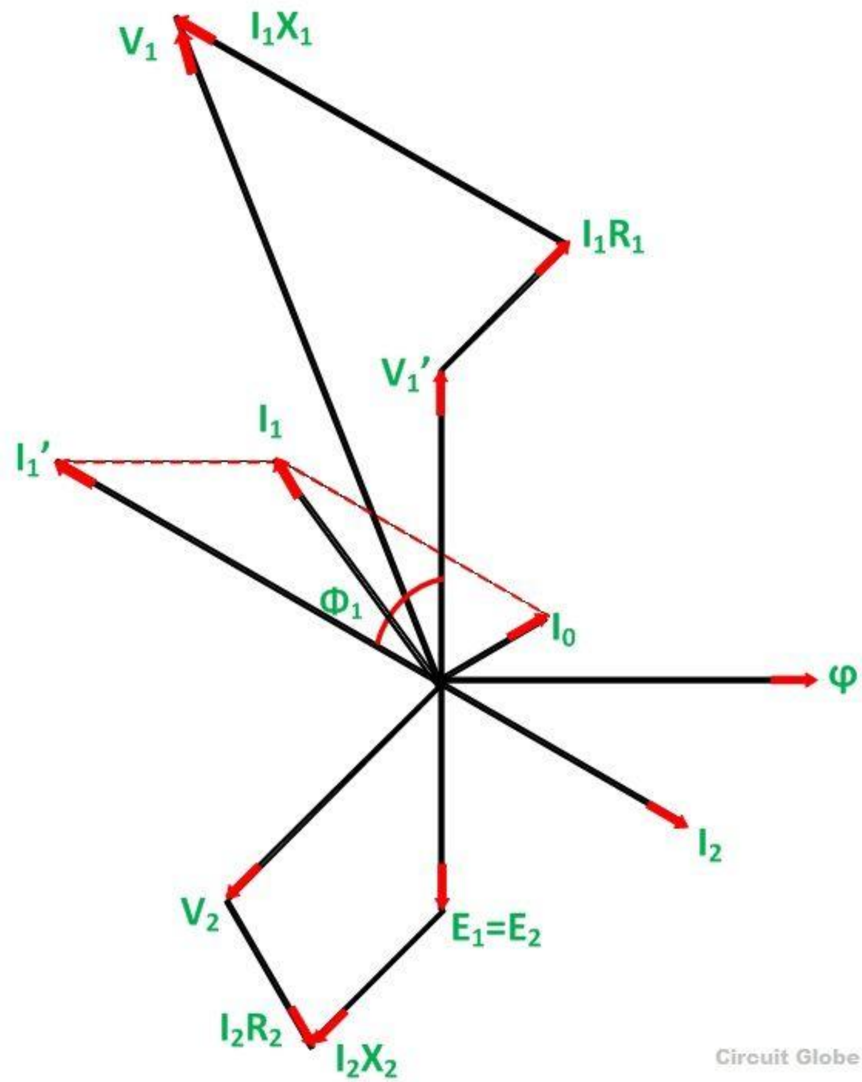
- Current I_1' is drawn equal and opposite to the current I_2

- The total current I_1 flowing in the primary winding is the phasor sum of I_1' and I_0.
- Primary applied voltage V_1 is the phasor sum of V_1' and the voltage drop in the primary winding.

$V_1 = V_1' +$ voltage drop
I_1R_1 is in phase with I_1 and I_1X_I is in quadrature with I_1.

- The phasor difference between V_1 and I_1 gives the power factor angle ϕ_1 of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.

This is all about the phasor diagram on various loads.



Phasor Diagram of the Transformer on Capacitive Load